(1)

PL-TR-94-2067

Space Debris Detection and Analysis

Robert H. Eather
Ron Siewert

Keo Consultants
27 Irving St.
Brookline MA 02146

28 February, 1994

Scientific Report No. 1

Approved for public release; distribution unlimited

PHILLIPS LABORATORY
Directorate of Geophysics
AIR FORCE MATERIEL COMMAND
HANSCOM AIR FORCE BASE, MA 01731-3010

"This technical report has been reviewed and is approved for publication"

(Signature)
PHAN DAO
Contract Manager

(Signature)
DAVID N. ANDERSON
Branch Chief

(Signature)
WILLIAM K. VICKERY
Division Director

This report has been reviewed by the ESC Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS).

Qualified requestors may obtain additional copies from the Defense Technical Information Center (DTIC). All others should apply to the National Technical Information Service (NTIS).

If your address has changed, if you wish to be removed from the mailing list, or if the addressee is no longer emloyed by your organization, please notify PL/TSI, 29 Randolph Road, Hanscom AFB, MA 01731-3010. This will assist us in maintaining a current mailing list.

Do not return copies of this report unless contractual obligations or notices on a specific document requires that it be returned.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
28FEB94

3. REPORT TYPE AND DATES COVERED
Scientific No.1

4. TITLE AND SUBTITLE
Space Debris Detection and Analysis

5. FUNDING NUMBERS
PE61102F
PR 2295 TA 24 WU AR
Contract:
F19628-92-C-0070

6. AUTHOR(S)
Robert H. Eather
Ronald Siewert

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Keo Consultants
27 Irving St.
Brookline MA 02146

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Phillips Laboratory
29 Randolph Rd.
Hanscom AFB MA 01731-3010
Contract Manager: Phan Dao / GPIM

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
PL-TR-94-2067

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release;
Distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

A 16" telescope with an image-intensified CCD camera has been deployed for testing for space debris detection. Sensitivity calibrations will take place after the ODERACS mission deploys calibration spheres from the Space Shuttle. An image analysis facility has been set up at Phillips Laboratory, and appropriate software written for image digitization and analysis. Various algorithms to extract low-level debris signatures from the night-sky background have been investigated. A model has been developed for debris population prediction from a known starting population distribution.

14. SUBJECT TERMS
Space debris

15. NUMBER OF PAGES
20

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	SAR

Table of Contents

1. Introduction:

The aim of the space debris detection and recognition project is to optically detect and track space debris of a size that radar is unable to detect (<10 cm). The contract as originally negotiated had three main objectives:

(i) To build a second optical detector (similar to that built under Contract F19628-91-C-0054) for installation at an astronomical site (e.g.. AMOS in Hawaii)

(ii) Software development for debris track identification and analysis. The objective is to devise computer techniques to search images in a semi-automatic fashion.

(iii) To set up a central image analysis facility at Phillips Laboratory to analyze debris video tapes.

Because this is a development program, it was expected that results obtained along the way may well lead to changes and/or modifications to these objectives.

In the first Quarter, we examined the specifications for the AMOS telescope in Hawaii, and anticipated no problems in integrating an intensified camera to the telescope. However, Air Force arrangements had not been made to use this telescope at that time. During the third Quarter, it was decided by the Air Force to curtail the observational program, so as to emphasize analysis of existing data sets, and extend theoretical analyses. Consequently Objective 1(i) above will not be pursued at this time.

A 16" Newtonian telescope with an image-intensified CCD camera, (mounted on a manually operated azimuth-elevation mount) was constructed under an earlier contract, and used for debris observations from Haystack Observatory (near Boston). This telescope was then installed at the Rattlesnake Observatory for the ODERACS experiment, which failed to deploy from the Space Shuttle in December, 1992 (see Appendix). We stored the telescope at Rattlesnake in anticipation of ODERACS rescheduling in February 1994, and in anticipation that this contract will fund a field trip to the observatory at that time.

Work on the development of an image analysis facility at Hanscom proceeded early in the contract, but was then put on hold because of the curtailing of the observational program.

In the first quarter of 1993 focus shifted to a modeling effort, based on data obtained from other observation centers. Specifically, the modeling effort was concerned with the determination of the spatial density of the debris clouds. The modeling effort was continued until September 30, 1993.

2. Initial research:

The first task was to familiarize ourselves with the current state-of-the-art in streak detection. We reviewed a report published in 1987 and written by P. Chu of Lincoln Laboratory called the SBV algorithm and titled "Detection of Small Moving Objects". This algorithm proposed using a "projection method" to reduce the dimensionality of the huge amounts of data involved. This proposal was backed up by analyses that showed these projections were valid for representing the data without loss of relevant information. However, this algorithm involved a two-step process and we were looking for a real-time response system. SBV was informative insofar as outlining possible methods with which to attack the massive amounts of data.

Additionally, we would be working in a very low *signal-to-noise* ratio (S/N) and therefore a thorough understanding of state-of-the-art noise removal techniques is essential. The major thrust in this field has been using median filtering methods because of the "impulse noise" at the detector. Median filters have the attractive property of suppressing impulse noise while preserving edges. The median filter, however, does not preserve thin line details (TLDs) such as space debris streaks. Because of the TLD problem many researchers are investigating hybrid median filters such as: combination median filters (CM), multilevel median filters (MLM), and single adaptive median filters (SAM). The CM incorporates the MLM and the normal median filter, as well as a directional median filter and proved to be of possible use. The main idea of a median filter is in taking a block of pixels and setting each of those pixels in the block to the value of the median of the group. The statistical median is much less sensitive than a statistical average would be because an extreme value isn't going to affect the median pixel's value whereas it would affect a statistical average value. Therein lies its value as a filter to smooth radical outlying values.

3. Debris Telescope:

An image-intensified CCD imager, coupled to a 16" telescope with a 2° field-of-view, was available from an earlier contract (see Figure 1). Also available was a manually controlled azimuth/elevation mount, with scale readout of the azimuth and electronic inclinometer readout of elevation. In order to transport the telescope and mount, we had two foam-lined shipping boxes made that could withstand the rigors of transportation. The telescope mount could be placed in one box in an upright position while the telescope was laid in a horizontal position within the other box. A third shipping box for the electronics rack was available from the earlier contract.

Site evaluation determinations considered the extreme light pollution in and around the Boston metropolitan area. Due to driving time from Phillips Laboratory and considerations of available space and authorization, we settled on Millstone Hill in Westford, MA as the best site. We were able to place the equipment in a secure building in the middle of a clearing that provided near horizon visibility. The darkness of the sky wasn't as good as for an astronomical site, but was sufficient for the initial calibration and tracking phase.

4. Image Analysis Lab.:

One of the thrusts of the space debris detection and recognition project was to establish an image lab which would allow personnel to easily digitize and process space debris data at Phillips Laboratory.

The following video equipment was purchased:

1. Panasonic AG-7750 S-VHS Recorder/Player with AG-F700 Time Code Inserter/Reader
2. Panasonic AG-7355 S-VHS Recorder/Player (with frame store) and AG-232TC interface.

Initially, we purchased a computer to perform processing and noise removal of images that were acquired by the 16" telescope. The computer chosen was a Gateway 2000 80486 running at the clock doubled speed of 50 megahertz. The fast personal computer speed was needed to facilitate computationally intensive image processing algorithms such as noise and clutter removal. Additionally, we needed an interface to the optical detector that could store CCD video images for off-line processing. The items purchased to accomplish the video

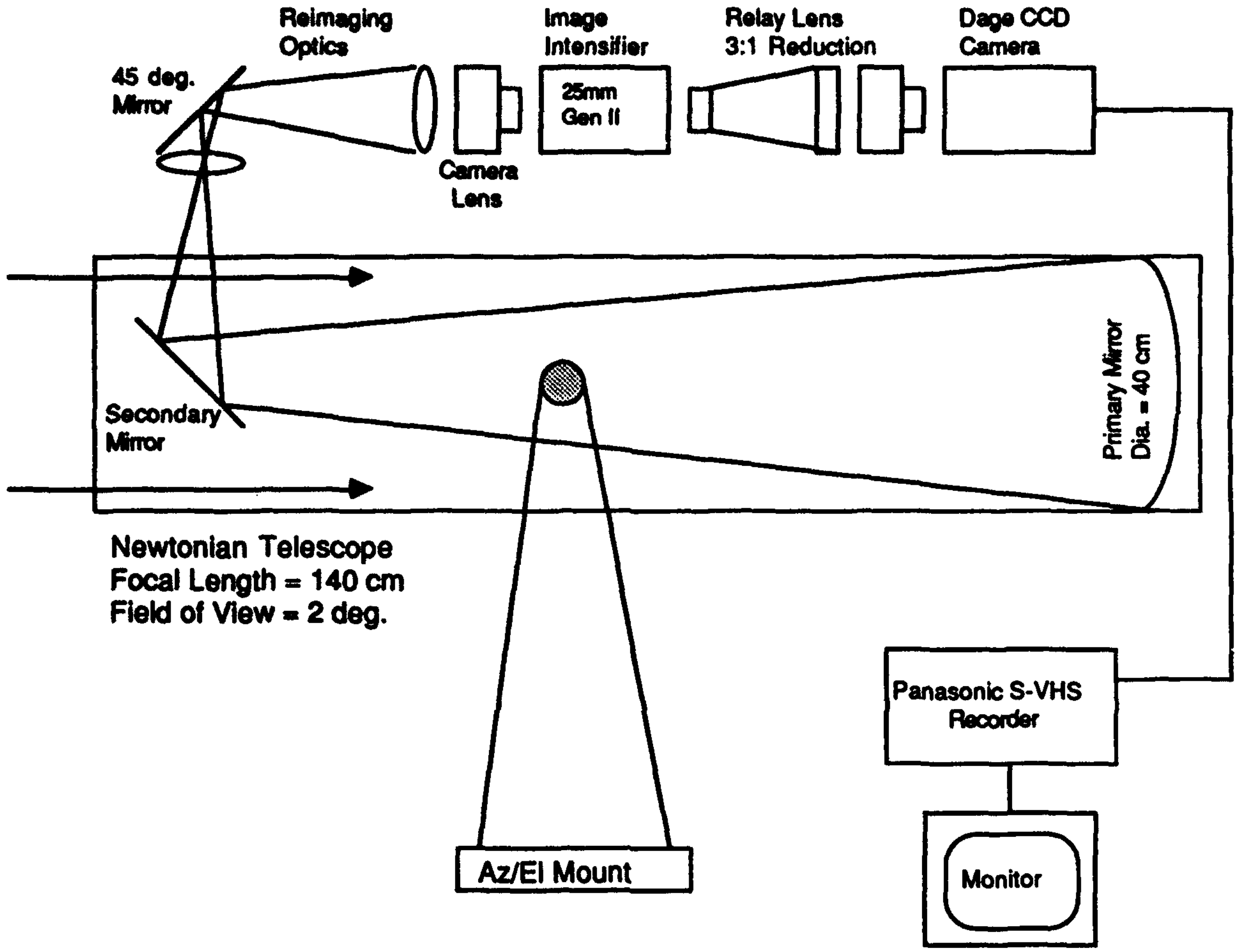


Figure 1: Schematic of telescope and data recording system

acquisition and storage were a Panasonic AG-7355 S-VHS VCR with built-in frame store. Also, to facilitate easy location on the video tape of space debris streak data we purchased an AG-232TC serial interface accessed by the computer serial port. The time code was stamped using a Panasonic AG-F700 time code generator/reader. To complete the acquisition package for data analysis we purchased an overlay framegrabber from Imaging Technology to digitize the video data.

To accommodate the large storage needs for digitized images we purchased a Wangdat digital audio tape (DAT) with storage capacities of 2MB uncompressed and 4MB compressed.

To make the lab user friendly, we had to consider operating environments used by personnel most likely to use the lab for processing purposes. Once the equipment was in place to accept S-VHS tapes from the optical site, applications were written to provide the capability to control the tape deck. We wanted to control the digitizing of the images, and provide certain Boolean operations on the digital image. Some time was spent interfacing the computer to the tape deck. The initial controlling operations: forward, backward, rewind, fast forward (i.e. command operations) were implemented easily. We still wanted the capability to direct the tape deck to go to a certain time stamp on the tape. Hence, Panasonic (Representative Neil Ugo) worked with us towards this goal. Panasonic initially sent Keo the programs that Panasonic uses to give demonstrations for the tape deck we were using. The program was not suitable for our applications. The time stamp command would freeze the machine necessitating a cold reboot. The next version of Panasonic's program actually printed out the time code stamps as the tape was being played or rewound. The readings were inconsistent and illogical. Hence, the time code stamp generating unit was apparently not working. Unfortunately, the data acquisition tape deck was on Rattlesnake Mountain in Washington State and could not be tested. Therefore, the resolution of this issue has to wait until the detector and equipment can be retrieved.

All pertinent Boolean operations (XOR, NOT, AND, etc.) were implemented to be able to process digital space debris images for more streak information. These operations were implemented in a C program that took command line arguments to determine which Boolean operation to perform.

Several applications were also written to provide the basic functionality of digitizing, writing captured images to disk, and reading them back again. All these applications took command line arguments providing increased flexibility. The digitization application could grab one video frame or a user-specified number of frames. Additionally, the read from disk application could read one or many files at each invocation.

5. Supporting Software Applications:

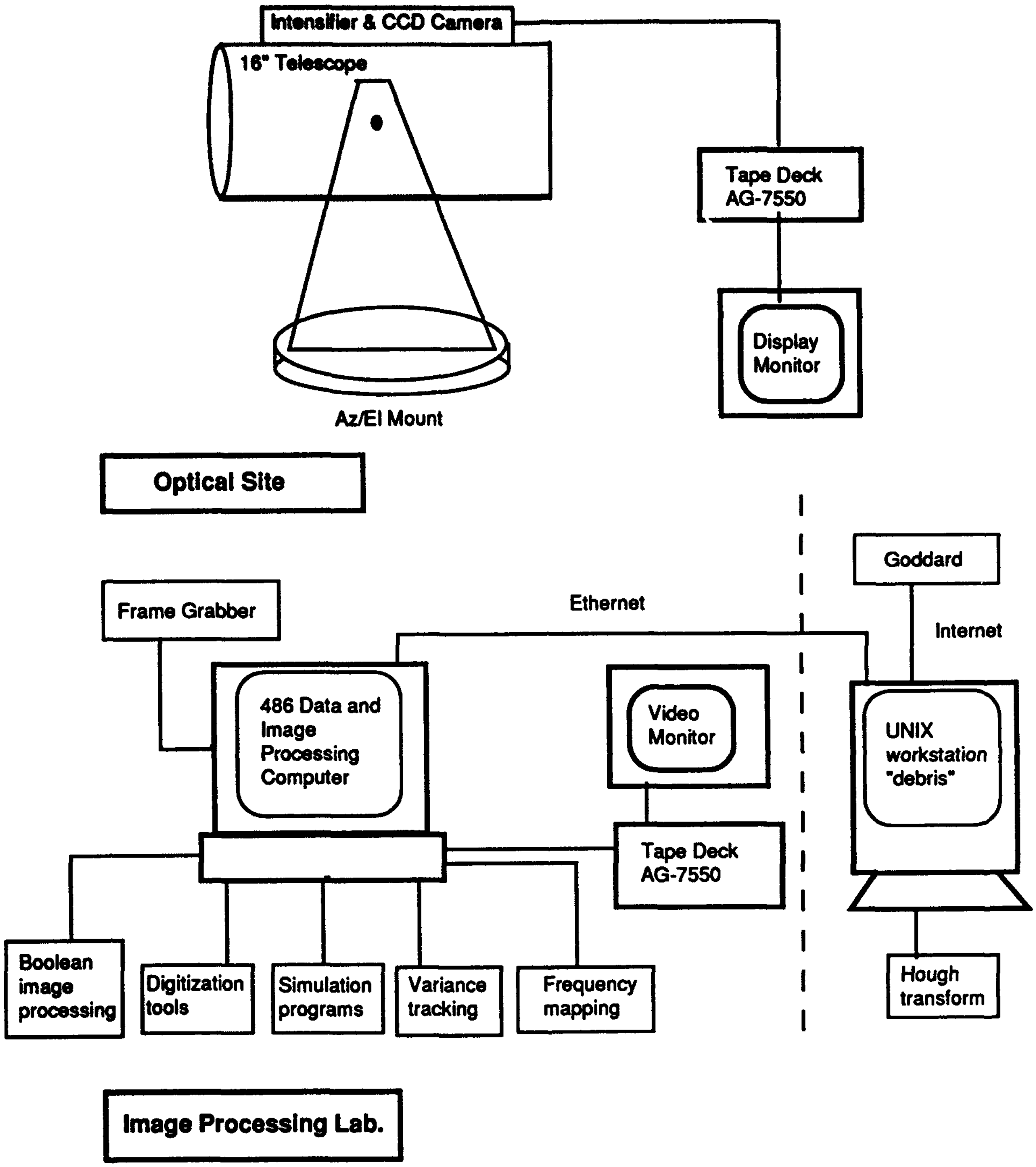
To allow the above hardware components to work together we investigated and purchased certain software applications. Software of varying levels of sophistication and price to support the framegrabber was investigated from many vendors. Some applications provided a WINDOWS' graphical user interface (GUI) with many image processing functions. Other applications were more focused on certain image analysis algorithms. After evaluation it was decided that for our specific needs these applications contained many functions that we would be paying for but weren't needed. Hence, we decided that it would be better to write our own *applications using the* ITEX *image processing* library from Imaging Technology.

Additionally, a first version of a program to serially interface the controlling computer to the Panasonic AG-7355 was written in anticipation of the need to drive the VCR via computer in order to locate time-stamped video frames.

An outline of the debris data collection and analysis procedure is shown in Figure 2.

6. Video Tape Analysis Procedure:

Test data that had been acquired was taken back to the lab for further processing. The S-VHS tape was placed in the AG-7355 and advanced to a location on the tape (noted during on-site acquisition) where a debris object had crossed the field-of-view. Using an astronomy program called "The-Sky", we located the star field corresponding to the frames containing the debris object. Evaluations were made as to the debris object's altitude and azimuth readings by comparing to the background star field.



Data Acquisition and Processing Procedure

Figure 2 - Debris data collection and analysis procedures

The tape data was digitized on a frame-by-frame basis with each frame stored in a separate file. For a typical debris object this procedure would generate about 90-200 files of one-fourth megabyte each. The digitized data files were first stored to the DAT before any processing occurred. Refer to the following data acquisition procedure diagram for associated components.

7. Data Preprocessing:

After digitization, the data files were in a format used by Imaging Technology. The format consisted of a header with various fields dedicated to image parameters. The remainder of the file consisted of the image data.

We needed the ability to process our data on our 80486 or the project SPARCstation, code-named 'debris', which contained certain signal processing applications. A program was written to give us the capability to use a program called Interactive Data Language (IDL) that resided on 'debris'. We wanted to use IDL to fill any gaps in desired image processing algorithms that would take too long to develop on our own. Consequently, to use IDL we needed the capability to transfe. files over the network. Additionally, the data files had to be translated to the tag image file format (TIFF) in order to be used on "debris". The first prerequisite was provided by the FTP protocol while the second requirement was provided by a program we wrote called image2tif.c. This program translated image files from Imaging Technologies' image format to the TIFF format.

8. ODERACS Project:

We became involved in the ODERACS task because of the need to calibrate the optical detector for space debris. The mission involved releasing six spheres: two 6-inch, two 4-inch, and two 2-inch. The spheres vary in their reflectivity, metal and size. These were to be used to calibrate received signals and as a comparison between optical and radar measurements.

The project Principal Investigator and Senior Software Engineer packed the detector and mount for transport and shipped it to Seattle, where they picked it up and trucked it to Richland, WA for installation at the Rattlesnake Mountain Observatory of Battelle Pacific Northwest

Labs. Pointing calibrations were made by sighting on known stars and comparing their altitude and azimuth, given by "The-Sky" astronomical program, with that of the altitude and azimuth readings given by the telescope mount. The mount was aligned so that it could be set in azimuth and elevation with an accuracy of about 0.25 degrees.

The ODERACS mission failed to be deployed in December, 1992 due to battery failure of the container lid mechanism. The experimental set-up was stored at Rattlesnake for the next ODERACS mission (see Appendix).

9. Analysis of Video Debris Data:

(a) Algorithm Research:

Research was carried out to determine successful algorithms to use for processing the digital images for streak information. Some of the research was accomplished at the Geophysics Laboratory Library. Internal reports by Lincoln Laboratory as well as familiar books on image processing were used. Also, discussions with personnel from The Analytical Sciences Corporation (TASC) proved to be very useful.

All of the algorithms that went into the successful implementation of the image lab were written in the C/C++ language using the Microsoft C/C++ version 6 & 7 compiler. After these modules were compiled and linked into executables they were included as program item icons under the Windows operating system. These programs were then able to run in a DOS window.

The algorithms that were used for image processing were developed or adapted for use on the Space Debris Detection and Recognition project. The frequency method is a technique described in various image processing texts. This algorithm was implemented under the statistics package 'MATLAB' as this package has excellent speed for such computationally intensive procedures as a Fourier transform poses for a data set of anything other than small size. The variance method was developed by the senior software engineer on the project while the Hough line transform method was implemented by personnel from The Analytical Sciences Corporation (TASC).

(b) Algorithms Tested:

(i) Frequency method:

The frequency method was developed to determine if there were any changing components in the scene being analyzed. The method is implemented by summing each column of pixels to reduce the dimensionality from two to one leaving us with a one-dimensional array of intensity values. The one-dimensional array is then mapped to a set of exponential functions and then transformed into frequency-space by the Fourier transform. This procedure is done on a frame-by-frame basis allowing for a output of frequencies of changes to the set of frames. If there is a change of intensities (meaning a moving object) in the set of one-dimensional arrays then that information is described by a frequency histogram with non-zero components. From those frequencies a determination can also be made as to the velocity of the object. However, this method was very susceptible to noise, both from the detector and the clutter background, and was to unstable for practical use.

(ii) Variance method:

Another method, termed the variance method, involves looking at statistics of differenced frames. A large variance value usually indicates where the debris object is located since the clutter is close to the mean of the differenced frame. Hence, the variance graph showed a relatively high peak at the position of the debris. Once in a while a clutter object (star) would move just enough to allow some high peaks at the clutter movement positions in the variance plots. However, these would soon die out and the differenced debris object's variance would again be the maximum value of the vector. Hence, by keeping track of the x,y positions of the maximum value of the variance vectors one can put together a track of the object's motion.

(iii) Hough line transform method:

The Hough line transform method, proposed and implemented by members of The Analytical Sciences Corporation (TASC) was the technique adopted by Phillips Laboratory personnel. The basic idea

behind the Hough transform is to map a line's parameters (slope and intercept) to a slope-intercept space. Since a debris object creates a 'streak' in the field-of-view (FOV), its line parameters could be mapped to a point in slope-intercept space. As each point of the line has the same slope-intercept parameters these will be mapped to the same point in the slope-intercept space. By thresholding that slope-intercept point one can determine if a 'streak' is present in the FOV. The algorithm was implemented on Sun workstations and proved to work well under high signal-to-noise scenarios. Research into the lower S/N ratios was being performed when the project shifted focus to spatial density modeling causing the Hough research to be put on hold.

10. Spatial Density Modeling:

(a) Objectives:

We performed a simulation of expected values of potential sightings of space debris objects based on a known compilation of starting values and then extrapolating the orbital parameters to the next set of values over a selectable time interval (normally two days). We wanted to see how the expected values we compiled correlated with the actual values received from the participating sites, AMOS (Hawaii) and Soccorro, NM. The procedural flow is shown in Figure 3.

(b) Two-line element sets:

The first task was to compile a good sampling of the tracking data output by Space Command. We wanted to achieve a representative sample of the population that we were dealing with. Goddard Space Flight Center posts "two line element sets" for acquisition by research sites that have a need for such information. These data sets are posted on a VAX computer and accessed by File Transfer Protocol (FTP) for downloading.

(c) Automated element set acquisition:

In order to assure a continuing and non-interrupted sequence of data sets we automated the acquisition process by a series of UNIX c-shell scripts. The data sets were posted on Monday, Wednesday, and

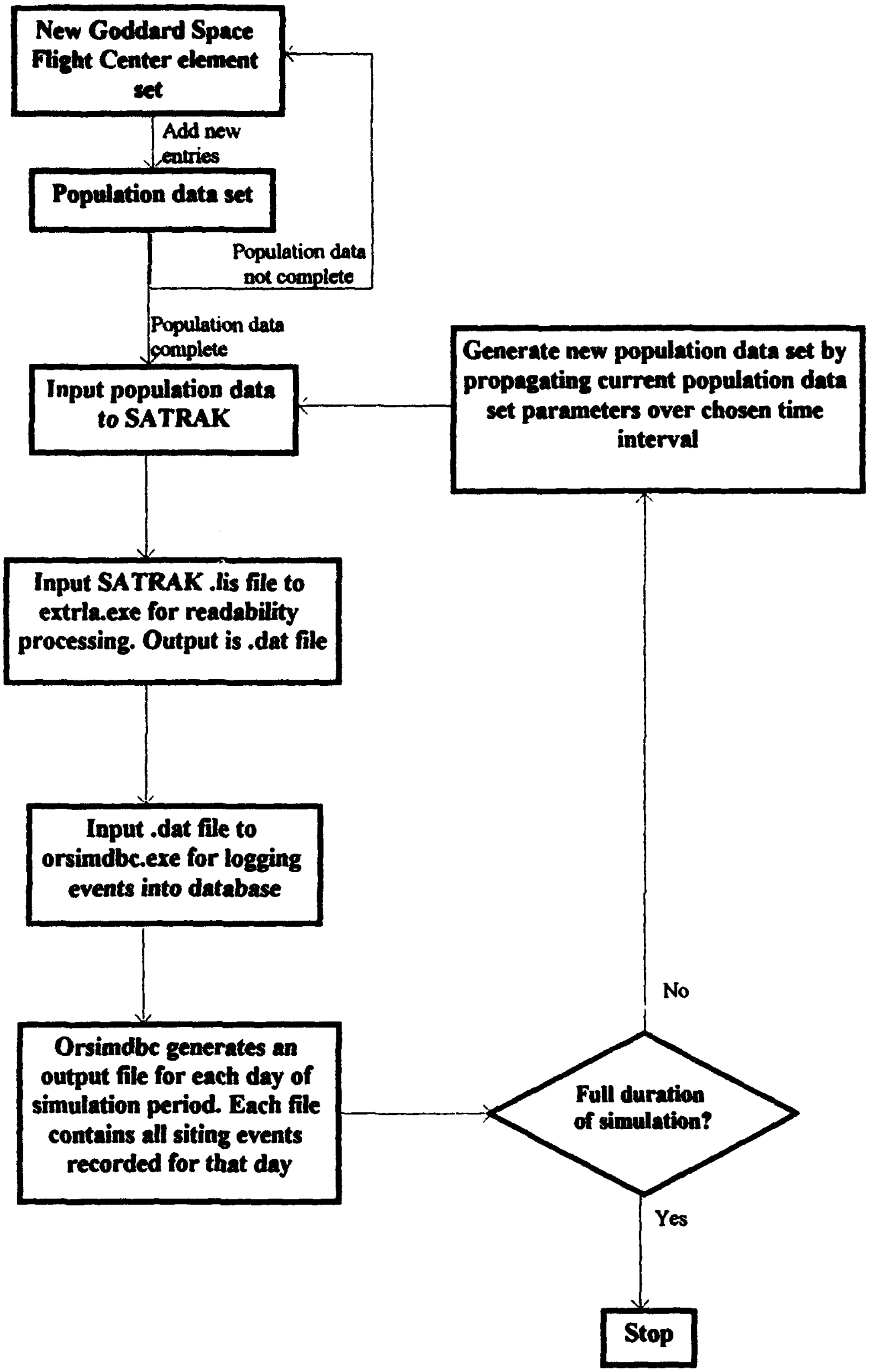


Figure 3: Procedural flow of spatial density modelling

Friday of each week. At 6 PM on those days the UNIX daemon process would wake up and log on to the VAX computer at Goddard, retrieve the current data set and log off. The automatic process would then compress the downloaded data set and go back to sleep.

(d) Software Components Setup:

The population data was compiled by starting with an arbitrary data set and moving forward in time adding those debris objects that were not already in the set. A series of applications have been written for the orbital debris statistics simulation. The simulation is coded in the object-oriented language, C++, which gives us greater flexibility, reusability, and robustness. A satellite tracking program, SATRAK, in conjunction with the element sets propagates the orbits of each debris object to some later time for observation, further tracking, or analysis. In the orbit simulation, we start with an initial element set's values and propagate the parameters that would change under normal conditions (dynamic parameters) for each debris object. After the first iteration, we have another element set of all the debris elements contained in the first set. The new set's elements have modified values for each of their dynamic parameters representing the changed state of each debris object. This process consisted of adding two days to the epoch time and modifying mean anomaly and mean motion to reflect the new orbital point in time. Using the March 5, 1993 element set as the initial population, each subsequent set was derived from the initial set by updating (modifying) certain parameters contained in the set. At the end of the process, we have two-line element sets for all the debris objects contained in the initial set, propagated over any interval we choose. The next step of the simulation is to input each of the element sets into the satellite tracking program. The tracking program outputs one list file for each detector site of interest. The list file contains the debris objects and the parameters necessary to observe each one as they pass within viewing range for the user-designated site. The list file's parameters give the necessary information, in raw form, to compile distribution statistics on the debris population. The list file, in turn, is processed by extrla.c (extract look angles). The output of extrla.exe (.dat file) is a more readable file than the aforementioned list file and presents the

parameters (altitude, azimuth, and time) necessary for locating the debris objects during a morning or evening viewing session. Extrla's output file is processed further by the program orsimdbc.exe (orbit simulation database create). Orsimdbc.exe extracts information from the two-line element file and extrla's .dat file, for each object that can be observed from a particular site, and appends that potential observation to a file named for the day that the observation occurred. The program appends current data to previous data in each day file if any exists, otherwise it creates the file. Preliminary results were analyzed for a twenty-day period to establish the validity of the model. The analyzed results agree with expected values.

(e) Data analysis:

We received space debris tracking data from the AMOS site in Hawaii and the Soccorro site in New Mexico. The purpose of this data was its use in comparisons between actual tracking and the spatial density simulation mentioned previously. We wrote several programs to massage this data. The first program processes data received from space debris observation and tracking sights, AMOS and New Mexico. The textual data are in individual files, each representing a night's observations. The file name encodes the type of file (coverage, B3, brightness, or element set), the year, and the location of the observations. The output file names combine these fields to identify the file type and location and are then used as inputs to a data analysis program. The second program performs essentially the tasks of the first except on a different format. That program also takes a number of text files of arithmetic data adding, modifying or eliminating fields in each file and then combines each into a file that is used as input to the same analysis phase.

The simulation was terminated after the 42nd update to the original element set. Data analysis was carried out for inclination, semi-major axis, and eccentricity. Histograms were calculated for ten-day intervals from day 10 through day 80 for each of the parameters. Each of these graphs contained two plots for comparison: the simulation data and the population data. Additionally, for 20 day intervals starting from day 20 through day 80 a correlation coefficient was computed and

plotted for each interval. The correlation coefficient gave a quantitative measure of the agreement between the simulation data and population data histograms at each 20-day interval. Generally, these plots were monotonically increasing and thus showed the convergence between the simulation and the population data.

11. Future Work:

Future work on this contract is uncertain because of changing priorities and possible funding cutbacks. However, it is expected that efforts will be spent in the following areas:

(a) Software for user-friendly interface between debris analysis software written by TASC, and the PL/GPIM Sun workstation.

(b) Investigation of fast signal processing hardware options for processing debris data.

(c) Participation in the ODERACS project when the spheres are successfully launched (see Appendix).

Appendix - ODERACS Experiment

During the period between the submission and editing of this report, the ODERACS deployment was successfully accomplished. We carried out successful observations of the 4-inch and 6-inch spheres from Rattlesnake, and these data are described in a summary report submitted to the Contract Monitor in March, 1994, and also in Quarterly Report Keo-08.